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CO₂-EXCITED LANGMUIR TURBULENCE IN A DENSE PLASMA FOCUS.(U)

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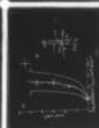
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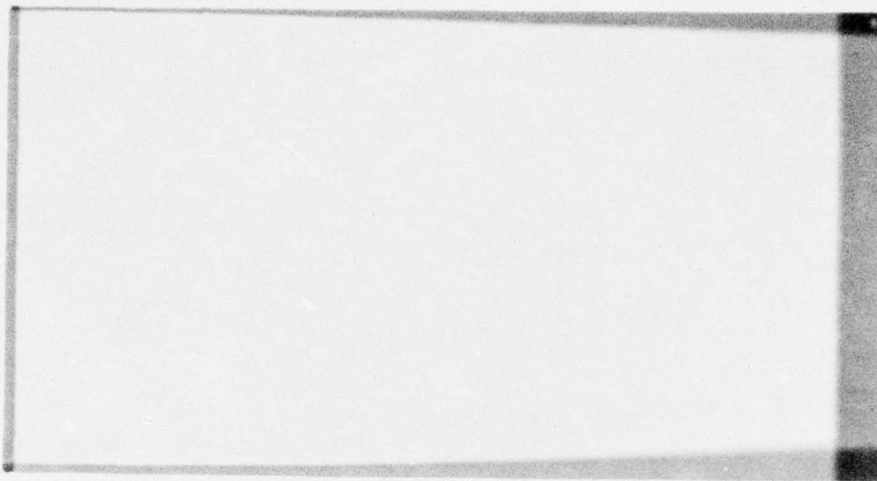
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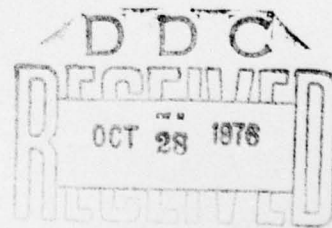
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IN A DENSE PLASMA FOCUS

M. J. Forrest, P. D. Morgan, N. J. Peacock,
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**CO₂-Excited Langmuir Turbulence
in a Dense Plasma Focus**

M. J. Forrest, P. D. Morgan, N. J. Peacock, K. Kuriki*

Euratom-UKAEA Association for Fusion Research,
Culham Laboratory, Abingdon, Oxon OX 143DB U K

M. V. Goldman[†] and T. Rudolph[†]

Department of Astro-Geophysics, University of Colorado

Boulder, Colorado 80309

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ABSTRACT

We report on ruby-laser scattering measurements of Langmuir turbulence excited in a high-density plasma by a CO₂ laser pump. The observations can be explained by a new treatment of the convective electron-ion decay instability at equal temperatures.

Recently, there has been a great deal of experimental activity^{1,2} devoted to plasma properties in the vicinity of the critical surface of laser-irradiated high density plasmas. Among the diagnostics that have been employed are single-laser reflection,¹ and harmonic light emissions.² In this letter we report direct observations of a decay parametric instability³ driven by a TEA CO₂ laser pump near the critical surface of a separately created high density plasma. The principal diagnostic is incoherent scattering performed with a second (ruby) laser. We believe that incoherent scattering can offer added flexibility and control in comparison with other diagnostic methods for measuring Langmuir turbulence of laser origin in high density plasmas.

In addition, a theory of the ruby-scattering cross section is set forth, based on the linear convective electron-ion decay-instability at equal temperatures.^{3,4} The theory appears to account for most of the behavior of the cross section as a function of CO₂ intensity.

The deuterium plasma is created in a Mather-type dense plasma focus device.⁵ The measurements are made after the current sheet has run down the co-axial electrodes and the current has become mainly axial near the anode.⁶ In this "pinch" phase, the plasma resembles a Z-pinch, with density decreasing radially from a maximum at $r = 0$. Earlier experiments⁴ in this device have tended to show that the plasma is essentially quiescent in the radial direction.

The laser-plasma geometry is shown in Fig. 1. In Fig. 1(a) it is seen that the CO_2 and ruby beams are arranged co-axially with each other (AB axis), and orthogonal to the pinch axis (CD). The peak CO_2 output of 4.5 J average delivered in 40 nsec, is focused by a 27 cm Ge lens to a spot size of 750 μm . The 5J output of the ruby beam is delivered in 15 nsec, and focused with a 75 cm lens to a spot size of 0.25 cm. The collected scattered radiation lies in an annulus with scattering angles between 5.5° and 10.5° . The mask selects out only the radially-propagating Langmuir waves normal to the plane ABCD. This is also the direction of plane polarization of the CO_2 beam.

The scattered ruby light passes through an interference filter centered at 6500 \AA with 50 \AA passband. If the Langmuir frequency were exactly equal to the CO_2 frequency, the plasma line would be centered at 6515 \AA . The 50 \AA passband is too wide to distinguish between the plasma line structure and an offset from the CO_2 frequency by an ion-acoustic frequency (at most a few Angstroms).

The photomultiplier receives noise emission (mainly bremsstrahlung) from the plasma, as well as scattering from the Langmuir feature. In the absence of the CO_2 beam the Langmuir feature is not observed. A simple calculation of equilibrium scattering from Langmuir waves, in the scattering volume, V_{50} , associated with the 50 \AA passband, gives a cross section a factor of two below our experimental detection level. With a sufficiently intense CO_2 beam, and for the proper time-phasing of the lasers, the observed scattering can be up to 30 times the equilibrium level expected in V_{50} . We argue theoretically that the enhanced Langmuir waves originate in a volume, V_s , four orders of magnitude smaller than V_{50} .

The CO_2 and ruby pulses are synchronized to peak at various times in the radial compression history of the plasma. The Langmuir waves are only observed about 35 nsecs prior to peak compression (-35 nsecs). At this time, the maximum electron density is equal to $1.5 \times 10^{19} \text{ cm}^{-3}$, and we assume the CO_2 radiation is reflected. Radial and axial density profiles are measured by interferometric techniques, in the absence of the CO_2 beam. Time-dependent density profiles are constructed over many shots by Mach-Zehnder and holographic interferometry, and confirmed over a single shot by schlieren photography. This technique has been used before⁷ and yields reproduceable curves of $n_e(r, z, t)$.

From this we determine that the reflection point of a normally-incident CO_2 ray is $r_0 \approx 0.04$ cm, and that the electron-density scale-length $L \equiv n/|\partial n/\partial r|_{r_0}$ is about 0.20 ± 0.05 cm at the time, -35 nsec, when Langmuir waves are observed. Geometric optics predicts the locus of CO_2 ray reflection points indicated in Fig. 1(b).

Figure 2(a) shows the observed scattering cross section as a function of focused vacuum CO_2 intensity, I_{VAC} , at -35 nsec.

At times earlier than about 35 nsecs prior to peak compression, the density pulse has not yet converged to the axis, the maximum density is below 10^{19} cm^{-3} , and no scattering is observed, even with maximum CO_2 intensity. During the 35 nsecs just before peak compression, the maximum density is above 10^{19} cm^{-3} , and L decreases from 0.20 cm to 0.025 cm. No enhanced scattering is observed at peak compression.

At peak compression, the electron temperature is measured to be about 2 keV, by light scattering and by spectral line emission.⁸ At -35 nsecs, the electron temperature is calculated by assuming two-dimensional adiabatic compression. The local electron temperature is 870 ± 200 eV. From this and the mean scattering angle, $\theta_s = 8^\circ$, we calculate the scattering parameter $\alpha \equiv k_D/k \approx 11$.

The experimentally observed CO_2 "threshold" of $5 \times 10^9 \text{ W cm}^{-2}$ is about an order of magnitude above the threshold for the homogeneous electron-ion decay instability in the presence of equal electron and ion temperatures.^{3,4} We show next that a linear convective saturation theory of this instability is adequate to account for most of the experimental observations. The appropriate geometry is similar to that considered by Perkins and Flick,⁹ but their theory is only applicable

when $T_e \gg T_i$. In our WKB theory we employ a kinetic model of ions and take into account the important "beat" spontaneous emission⁴ of Langmuir waves. The details of the theory, and arguments for the absence of other Langmuir instabilities are given elsewhere.¹⁰

The integrated scattering cross section is given approximately by

$$\sigma = (r_e^2/\alpha^2) n_0 V_s \delta\Omega_s I, \quad V_s = \ell A_s, \quad (1)$$

where $r_e^2 = 5 \times 10^{-26} \text{ cm}^2$. The solid angle for scattering is $\delta\Omega_s = 6.5 \times 10^{-3}$ steradians. n_0 is the mean local electron density. V_s is the scattering volume, and ℓ is the axial length, equal to the CO_2 spot size, 750 μm . The cross sectional scattering area A_s is shown in Fig. 1(b). $I(\underline{k}) \equiv \lim_{V \rightarrow 0} \langle |\delta E(\underline{k})|^2 \rangle / 4\pi V \Omega$, is the spectral intensity of longitudinal field fluctuations around the plasma frequency, normalized to be one in equilibrium.

For theoretical simplicity, we straighten out the curved scattering volume in Fig. 1(b) into the slab geometry shown in Fig. 2(b). The x-direction is the direction of an assumed linear density gradient with scale length L . The CO_2 field is in the y-direction. In the Langmuir ray paths in Fig. 2(b) k_y is assumed to be a constant, set by the scattering geometry to be k_D/α . Also, $k_x = -\omega_0 t/2L$, and $x - x_0 = -(3/4)v_e^2 t^2/L$. ω_0 is

the CO_2 frequency, and x_0 is the Langmuir wave reflection-point.

Magnetic field effects can be ignored.¹⁰

Along a ray path, the steady-state kinetic equation for

$I = I(k_x(t), x(t); k_y, \omega_L)$ is given by¹⁰

$$(d/dt)I = 2\Gamma_g I + (I/t) + 2\gamma_c + (\omega_p/\omega_o - \omega_L)2\gamma_g. \quad (2)$$

The first term on the right-side is the net growth rate, $\Gamma_g = \gamma_g - \gamma_c$, where γ_g is the appropriate parametric growth rate,³ and γ_c is the collisional damping rate. The second term corresponds to first order WKB swelling of Langmuir waves due to the divergence of the group velocity. The third term is linear emission, and the fourth term is the dominant "beat" spontaneous emission, in which low frequency ion Cerenkov emission is upshifted in frequency by the CO_2 -pump, and becomes a source for Langmuir waves.

We integrate (2) from an initial time, t_1 , at which $\Gamma_g = 0$ (with the boundary condition $I(t_1) = 1$), to a final time, t_f :

$$I(t_f) = (t_b/t_f) [\alpha(m_i/m_e)^{1/2}/1.7] \exp[(5/256)Lk_y(\bar{E}_o^2/n\theta)] . \quad (3)$$

The exponentiation factor depends on the local mean (swollen) CO_2 field, \bar{E}_o^2 , which is related to the vacuum intensity, by $\bar{E}_o^2 = (16\pi\alpha/\sqrt{3}c)I_{\text{VAC}}$. Exponentiation has been allowed to continue to the reflection point. The factor $\alpha(m_i/m_e)^{1/2}/1.7$ arises from beat-emission. The factor (t_b/t_f) is due to Langmuir wave-swelling, which is allowed to continue up to the time at which WKB breaks down,

$t_f = t_{\text{WKB}} = -2(k_D L)^{2/3} / \omega_o \sqrt{3}$. t_b is the effective time at which swelling begins in the beat-emission source term. Numerical integrations¹⁰ give t_b on the order of $t_{1/2} = -(Lk_y / \omega_o) (\bar{E}_o^2 \omega_o / 32\pi n_0 \gamma_c)^{1/4}$, and t_b/t_f between 3 and 6.

The scattering area can be shown¹⁰ to be $A_s \approx 2\delta\theta_s r_o \delta r$, where $\delta\theta_s$ is the range of accepted scattering angles (5°). δr is determined by the time $t_{1/2}$ at which $I(t_{1/2}) = I(t_f)/2$, due to the combined effects of diminished swelling and exponentiation. Numerical results¹⁰ show that, for our parameters, $t_{1/2} \approx \sqrt{2} t_{\text{WKB}}$. The ray equation yields for this time, $\delta r = \delta x \approx 2k_D^{-1} (k_D L)^{1/3}$, which is numerically on the order of 5×10^{-4} cm.

Evaluating all the quantities in Eq. (3) with the experimentally determined scale length of $L = 0.20 \text{ cm} \pm 0.05 \text{ cm}$, a temperature of $800 \text{ eV} \pm 200 \text{ eV}$, and the frequency-matched density of $9.7 \times 10^{18} \text{ cm}^{-3}$, gives the theoretical curves shown in Fig. 2(a).

The nonlinear saturation time,¹¹ t_{NL} , due to induced-scattering off ions in a homogeneous plasma, can be estimated from the time-asymptotic analytic solution¹² and compared with the time available along the ray path. We find the two times are both equal to 0.04 nsecs when $I_{\text{VAC}} \approx 10^{10} \text{ W cm}^{-2}$. Thus, it is reasonable that the curve of $\sigma(I_{\text{VAC}})$ should cease to be exponential much beyond this intensity, and we anticipate that the point at $2 \times 10^{10} \text{ W cm}^{-2}$ requires a nonlinear inhomogeneous theory.¹⁰

The calculated threshold and its dependence on scale length is consistent with the experiment, and the inhomogeneous linear saturation theory appears to give a satisfactory fit to the data at CO_2 intensities, I_{VAC} , around $10^{10} \text{ W cm}^{-2}$ and below.

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- * Permanent address: Institute of Space and Aeronautical Science,
University of Tokyo, Japan.
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FIGURE CAPTIONS

Fig. 1. (a) Scattering geometry; (b) enhanced scattering volume.

Fig. 2. (a) The ruby scattering cross section as a function of the vacuum focused CO_2 intensity. Both experimental points and theoretical curves are shown. The solid curve, C , is for $L = 0.20$ cm, and $T_e = 800$ eV. The dashed curve C_+ (C_-) results from an increase (decrease) of L by 0.05 cm or a decrease (increase) of T_e by 200 eV. (b) Langmuir ray paths.

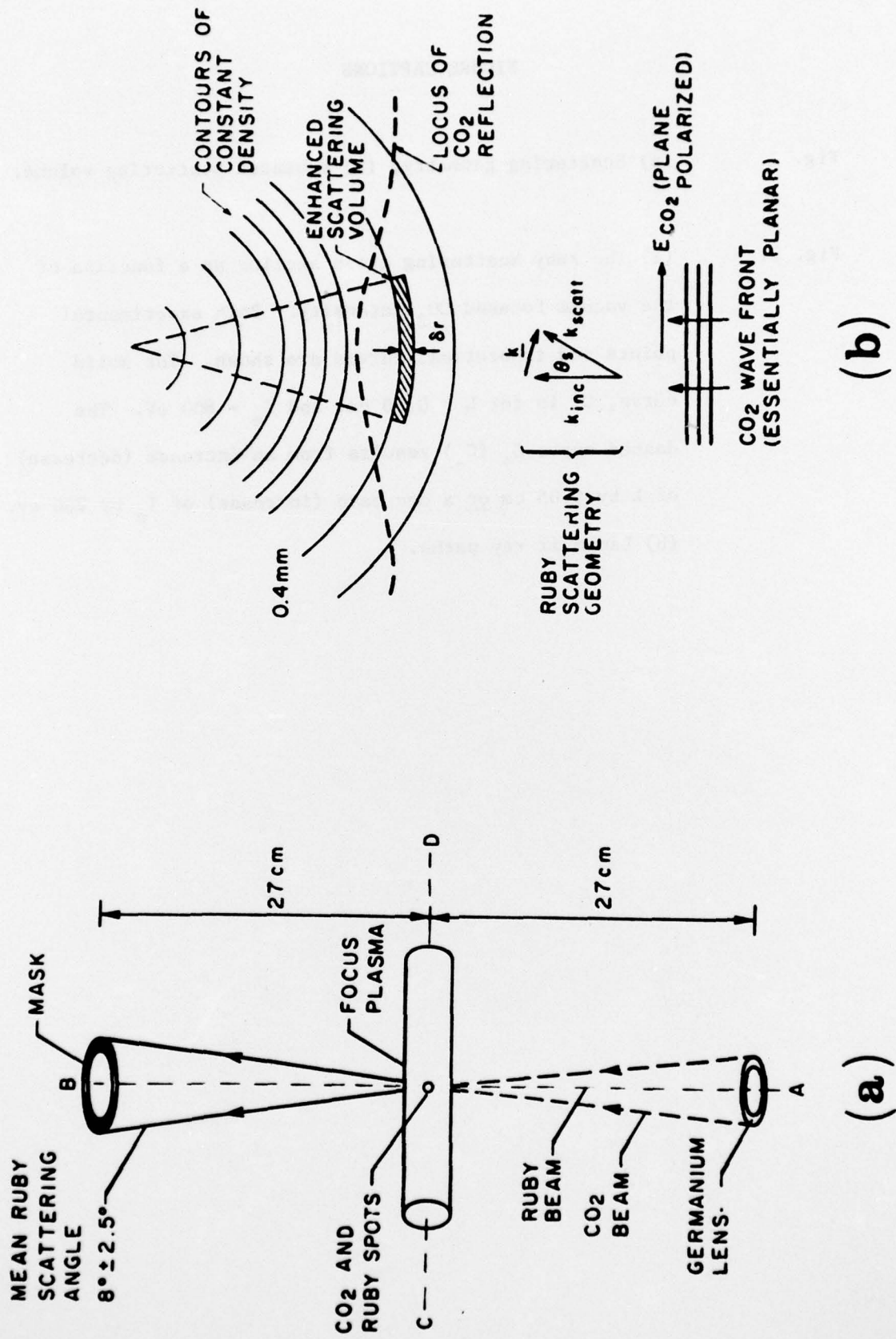


FIGURE 1

